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Inhalation Exposure of Lead in Brass Foundry Workers: The Evaluation of the Effectiveness of a Powered Air-Purifying Respirator and Engineering Controls

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Inhalation Exposure of Lead in Brass Foundry Workers: The Evaluation of the Effectiveness of a Powered Air-Purifying Respirator and Engineering Controls

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The protection that a powered air-purifying respirator afforded to ladle and furnace attendants who were exposed to lead, copper and zinc fumes in a brass foundry was found by measuring metal levels at the lapel and at nose level inside the respirator. Respirator fit was evaluated by use of a hot-wire anemometer at the face/Tyvek seal interfaces, and at the exit of the respirator. Effective protection factors for lead ranged from 1.05 to 67. Ergonomic factors and engineering controls are also discussed.

Introduction

The principles and use of respirators have been extensively reviewed.[1-5] Powered air-purifying respirators, which have found increasing use in the past decade, appear to have a number of potential advantages over negative pressure air-purifying respirators. Because the air is supplied at a minimum of 170 liters per minute (L/min), minor leakage should be of less importance, with leakage outward rather than inward. Thus, one would expect fewer fitting problems compared with those encountered by negative pressure respirators for heads with facial hair, scars, growths, wrinkles, sunken nose bridges, and the variations in face size and shape which normally require multiple sizes and brands of negative pressure respirators. Fewer problems should be encountered with talking, sneezing, coughing, smiling, laughing, or breaking the facepiece to face seal. Vision and communication should be improved and the resistance that many workers exhibit towards the uncomfortable and inconvenient negative pressure respirators should also be alleviated. Powered air-purifying respirators must meet the certification requirements,[6] that the odor of isoamyl acetate is not detected when test subjects perform designated exercises while exposed to 1000 parts per million of isoamyl acetate in a test chamber. (Filtered air is supplied to the facepiece, hood or helmet at 170 L/min.)

Fitting of respirators to individual workers is mandated by the Occupational Safety and Health Administration (OSHA).[7] The usual positive and negative pressure "quick checks" are not appropriate for those powered air-purifying units which do not provide a tight-fitting facepiece, and it is doubtful whether the irritant smoke qualitative test is commonly performed even when high efficiency filters make it practicable. Quantitative fit testing of negative pressure respirators is required by the OSHA standards for lead and acrylonitrile.[8] These standards also assigned a protection factor of 1000 to powered high efficiency air-purifying respirators. In contrast, the filters of non-high efficiency respirators are permitted up to 1.0% leakage of lead fume or silica dust in certification tests. Few tests of the performance of powered air-purifying respirators in the field have been published. We report here the performance of one such respirator, the Racal Airstream AH3 High Efficiency Air-purifying System. This respirator was evaluated for its effectiveness in protecting workers from lead fume under working conditions in a brass foundry.

Materials and Methods

The ladle and furnace room attendants of a production brass foundry which manufactured cast parts for subsequent machining were initially evaluated for their lead and other metal exposures, and for the protection afforded by a respirator approved for dust, fumes and radionuclides (Racal Airstream AH3 High Efficiency Air-purifying System - NIOSH/MSHA Approved TC-21C-212). Each filter is individually tested to be 99.97% efficient against a 0.3 μm DOP aerosol. The inlet flow rates vary from 6.5 to 8.0 cfm.[9] Personal breathing zone samples (lapel) and area samples were obtained utilizing calibrated Bendix C112 pumps (1 to 2 L/min) and 0.8 μm, 37 mm mixed cellulose ester filters.[10] Breathing zone samples from inside the respirator were collected on a 13 mm diameter Millipore SX00 1300 unit fitted with a 0.8 μm nominal pore size cellulose ester filter. The unit was anchored near the nose at the bottom edge of the respirator chin exit by two clips attached to the Tygon® tubing (1/4″ O.D.) which was fed through the air outlet of the respirator (Figure 1). The tubing connected the filter holder and the calibrated personal sampling pump (Figure 1). Lead, and in some cases copper and zinc, were measured by flame atomic absorption spectroscopy[11] as performed by a laboratory certified in industrial hygiene analysis.

Before and after sample collection, air velocities exiting the respirator were measured on some workers by a calibrated hot-wire anemometer (Anemotherm® Air Meter, Anemostat Corporation of America, NY). The air velocities where the face-mask met the face and in the mask exit under the chin were measured. In some cases, the velocities were increased by either changing the side shields or fastening

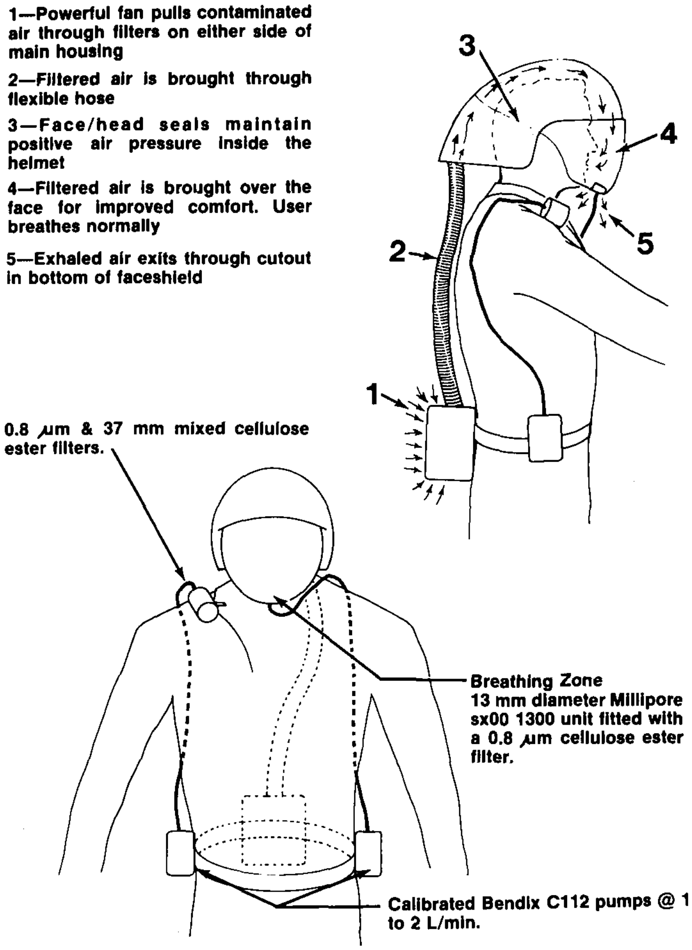

Figure 1 — Disposition of the personal samplers used to evaluate the positive pressure respirator.

them securely. These measurements were performed in a room air-conditioned at 24° C. Cross currents in the room were negligible as shown by the null reading of the hot-wire anemometer. Thus, deflections observed were truly indicative of leakage air.

Sample collection duration for furnace room attendants varied from 4 to 8 hours and included breaks and lunch. Measurements on ladle attendants were during the time of brass pouring (commonly 3 to 4 hours). The ladle attendants were followed to ensure they never raised their shields during their work cycle. Breaks were not included in the sample collection for ladle attendants. Thus, only the work motions contributed to any loss of protection afforded by the respirator for the ladle attendants..

Towards the end of this study, the newly available Racal Airstream AH3-1 High Efficiency Air Purifying System (NIOSH/MSHA Approval TC-21C-212) was also evaluated in the same manner. The major differences between the two models were the use of a Tyvek mask side seal to allow better fit at the side of the face and a different configuration of the battery terminals inside the filtration unit. The change in battery terminal configuration is reputed to increase battery life. To obtain the best protection factors, the leaks had to be plugged on an individual basis as indicated by the hot wire anemometry technique given above. The 13-mm sampler was not anchored to the exit of the respirator since the Tyvek mask seal supported the cassette without inconveniencing the worker. The cassette was connected to the plug by 1/8″ Tygon tubing adapted to 1/4″ Tygon connector tubing. In addition, a small, air conditioned, independently ventilated room was also constructed near the furnace for the furnace personnel for their rest and idling periods so that exposure to ambient lead in workplace dust, or in food or drink could be minimized. The rest of the foundry workers had a much larger but similar room for breaks. Extra Tyvek side seals were added to existing AH3 respirators in the light of early results for some furnace personnel. This configuration is equivalent to that in the new AH3-1 respirator in the area of the face shield, but is not the same as the AH3-1 with respect to battery terminal configuration.

Results

Table I shows the lead concentrations, protection factors, air velocities measured at the chin air outlet of the respirator, and relevant working conditions for the ladle and furnace room attendants for the two respirator models. The effective protection factor, being a function of use conditions,[19] should be a function of both the velocity measured at the chin exit and the proportion of time that the respirator face shield is down. The large independently ventilated room used for lunch breaks by all workers not working with leaded melts, contained air lead below the detection limit of ≤ 0.1 ppm. Outlet air velocities quoted are "at rest" before and after the strenuous work routine, and velocities during the work regimen would be less. With this in mind, there does not appear to be any significant protection when "at rest" outlet velocities are < 1 m/sec. Results for employee Number 6 were influenced by the frequency he kept his head shield up, he being relatively new to respirator usage. The higher lead values marked "a" in Table I were obtained before a lid for the lead ladle was fashioned to minimize lead fume. All the rest of the values were obtained with this engineering control. The ladle attendants did not have breaks during the sampling period, and always kept face shields down, so that their protection factors represent true protection factors. This was not so for the furnace attendants because of frequent raising of the head shield due to the dust and heat in the furnace room. Selection of the wrong side shields and the fact that the battery was not fully charged at the end of pouring caused the results in the third example for ladle attendant Number 1. Outlet linear velocities of 0.4 to 0.6 m/sec were associated with very little protection. All respirator flow rates were between 6.5 and 8 ft^3/min before and after brass pouring. The second sample for ladle attendant Number 2 allowed determination of the filter efficiency of the unit. Here, the protection factor for the sampling cassette placed at the top of the head where the purified air entered the helmet was > 97, demonstrating that the lower protection factors observed near the nose were not due to filter inefficiency when the respirator was set up as prescribed but due to inhalation velocity exceeding the velocity at the respirator exit. The bearded furnace attendant consistently

showed the lowest protection factors; however he often raised his visor. Except for the bearded worker, the protection afforded by the AH3-1 appears to be much better than that of the AH3. The use of an independently ventilated room for the furnace personnel to use during rest periods was clearly an effective engineering control to minimize exposures (Tables I and II), and, in fact, was the only successful way to lower the exposure of the bearded worker. This implies that much of the exposure in the furnace room before this control was instituted was caused by the breathing in of ambient dust particles from the dusty furnace room environment during the rest periods, when the worker raised his respirator shield.

Table II presents effective protection factors for three metals (lead, copper, zinc), analyzed from the same samples, and also compared with levels from area samples. As expected, furnace attendants showed consistently low protection factors for all three metals. The ladle attendants' protection factors, though higher, showed more variability (8 to 90). The AH3-1 respirator's performance is again clearly better. The protection for Zn is again much higher than for Cu or Pb. The large protection factor for zinc (1500) is also to be noted for the ladler.

Measurement of the leaks around the side shields and helmet borders via hot-wire anemometry revealed major areas of air leakage in both models. These occurred above the side shields at temple levels if the hard-hat/face shield seal was bad, and if the head-band was too loose. The AH3 model leaked substantially at the side shields also. These leaks constitute loss of protective power. Typically, velocities at temple levels for the AH3 were around one-third to one-half those at the central exit, and those at the lower face/side shield interface were one-sixth to one-quarter those at the central exit. In contrast, the velocities measured at the exit of the AH3-1 were approximately 5 m/sec, much higher than for the AH3. These velocities were expected to be higher due to the small holes in the Tyvek seal relative to the single large hole in the AH3 version. When the dimensions of the leaking openings were taken into account, it was found that the bulk of air loss occurred at the temples above the side shields. The velocity at the mask exit is, therefore, not only a function of the total inlet flow, but also of facial features, volume of leaks, and exit cross sectional area. The bearded furnace attendant (Number 4) consistently gave higher leakage rates at the beard/shield interface than clean-shaven workers, whether or not he wore the Tyvek seals.

TABLE I
Protection Factors: Lead Fume for Furnace Personnel at a Brass Foundry

Employee	Function	Pb Concentration ($\mu g/m^3$) Outside	Inside	A[A]	B[B]	Comments
1	Ladle attendant	356	-	-	-	No protection
		2316[C]	78	30	-	Long thin side shields; shield down continuously
		288	230	1.3	0.4 to 0.6 (end)	Wrong side shields; low flow caused by low battery
		530	19	28	5.6 to 7.6	Long thin side shields; shield down continuously
2	Ladle attendant	1217[C]	-	-	-	No protection
		485	<5	>97	-	Sample collected at purified air inlet
		800[D]	12	67	5 to 6	
3	Ladle attendant	320	57	5.6	1.5 to 1.8	Wide shields; shield down continuously
4	Furnace attendant[E]	184	-	-	-	No protection
		97	92	1.1	-	Shield up often; wide face
		190	160	1.2	0.7 to 1.0	Shield still up often
		196	70	2.8	2 to 3	Shield up less
		20[F]	8	2.5	5 to 6	Ventilated room for rest periods
5	Furnace attendant	84	19	4.4	1.7 to 2.0	Wide face; shield down continuously
6	Furnace attendant	46	25	1.8	7 to 12	Wide face; shield up often
7	Furnace attendant	36[E]	7	5.1	7 to 14	Narrow face; shield up often

[A]A = Effective protection factor.

[B]B = Face velocity at respirator exit (m/sec.)

[C]Before cover used on ladle.

[D]AH3-1 respirator (including rubber flaps).

[E]Beard.

[F]Tyvek side seal added to the AH3; rubber flaps retained.

TABLE II
Protection Factors of Lead, Copper and Zinc Determined Simultaneously on the Same Worker

		Concentrations in $\mu g/m^3$ (Protection Factor)							
		Pb		Zn		Cu			
Employee	Function	Out	In	Out	In	Out	In	A[A]	Comments
1	Ladle attendant	530	19(30)	6635	74(90)	21	2.8(8)	6 to 8	Long thin face; shield down continuously
2	Ladle attendant[B]	800	12(67)	9000	6(1500)	19	0.6(32)	6 to 9	Wide face; shield down continuously
3	Furnace attendant[C]	196 20[D]	70(3) 8[E](3)	400 125	170(2) 25[E](5)	58 6	19(3) 2.7[E](2)	2 to 3 2 to 3	Wide face; shield up intermittently
4	Furnace attendant	46	25(2)	162	41(4)	14	8.4(2)	7 to 12	Wide face; shield up often
5	Furnace[D,E] attendant	36	7(5)	215	9(24)	17	2.5(7)	4 to 6	Thin face; shield up often
6	Area sample in furnace	74		220		20.4			
OSHA Standard		50		5000(ZnO)		100			

[A]A = Face velocities at mask exit (m/sec).
[B]Independently ventilated room used during rest periods.
[C]Beard.
[D]AH3-1 respirator (including rubber flaps).
[E]AH3 equipped with Tyvek side seal; rubber flaps retained.

Discussion

The results in Table I imply that protection factors of the Racal Airstream AH3 respirator for lead fume under actual working conditions and utilizing the recommended operating conditions vary from 6 to 30 for ladle attendants experienced in the use of respirators. The AH3-1 respirator provided a protection factor of approximately 67. Effective protection factors for the furnace attendants varied from 1.1 to 4 for the AH3 respirator. With an added Tyvek face seal, making the respirator equivalent to the AH3-1 version, the effective protection factors ranged between 3 and 5. Laboratory data imply that protection factors for this respirator should be greater than 50.[1] The protection factors associated with actual working conditions are expected to be lower than laboratory generated safety factors. The ladle attendants' work routines are lively, with major motions being up and down and sideways. This particular ladle was constructed on a monorail system to facilitate the upright walking of the attendant during transfer of the unventilated ladle from the furnaces to the molding area. In the case of the furnace attendants, the liveliest motions occurred while shoveling scrap, and this involved the head being down with the respirator tending to hang vertically from the face. In addition, the hot dusty conditions often caused the attendants to raise their shields. All factors may contribute to the poor protection.

To protect adequately, the inward velocity inherent to inhalation must be surpassed by that of the supplied air at the hood exit; otherwise, contaminated air will be breathed in. Thus, it is recommended that personal breath velocities be measured by hot-wire anemometry to assess three conditions: at rest (velocities are about 1 to 3 m/sec), mild activity (walking 100 yards on a step ladder), and strenuous activity (running on the spot for 5 minutes). The exercises presently recommended by NIOSH for qualitative fit-testing are clearly inadequate to simulate the vigorous motions of the ladler and furnace personnel. Probably a safety factor of twice above the strenuous activity breath velocity should be attained by the respirator. Air losses due to leaks will detract from the potential protection. The leaks can be found by the simple, and effective hot-wire anemometer technique, and, thus, can also be used to optimize fit and design of the respirator. The leaks can be plugged on a personal basis, *e.g.*, by use of the Tyvek seals of the AH3-1, but the leaks above the side shields at temple level may require redesign of the respirator helmet to obtain adequate protection. Another theoretical solution would be to increase the flow rate toward the 15 cfm permitted from 6 cfm, an improvement of up to a factor of 2.5. Another solution is to decrease the diameter of the exit holes in the Tyvek mask, assuring higher exit velocities. Either worker rotation, dispensing with beards, or some engineering control may be eventually necessary for adequate protection. Obviously, the face shield should be down as much as possible. There is no doubt that the Tyvek side seal of the AH3-1 together with its small exit holes are major engineering improvements as proven by the enhanced protection factors, and the increased velocity of air at the respirator exit. However, it is evident from the present results that respirators alone may not provide sufficient protection during a vigorous work regimen. Intrinsically, further research to improve this type of respirator is worthwhile since powered air purifying respirators are much more flexible and comfortable in use than negative pressure varieties.

It is also evident that provision of a small, independently ventilated room is an effective engineering control for furnace personnel during their rest periods (Tables I and II). It is recommended that the furnace and ladle operators be kept separate from other foundry personnel during breaks, otherwise contamination of lunch rooms will eventually occur.

The results from Table II for the ladle attendants bear more discussion. The protection factors for Zn, as opposed to Cu and Pb are very dissimilar compared with those obtained for the furnace attendants. Theoretically, if all the fume has the same particle size, all the protection factors should agree, as generally occurs for the furnace attendants. The ladle attendant is exposed to the emission of the hot pot. Furnace personnel are exposed to the emissions of the furnaces and the dust of the furnace room during sweeping. Thus, the furnace operators will probably be exposed to particles of larger size. This should be shown directly in future research. In addition to this factor the collection efficiency of the filter cassette may vary with particle size and cassette orientation particularly at diameters $> 10\ \mu m$.[21] Metallurgical dusts and fumes have particle sizes ranging from 0.001 to 100 μm.[12] Zinc oxide fume is commonly in the size range 0.1 to 0.4 μm.[11] Lead smelter particles which consist of Pb, PbO, PbO_2, Pb_3O_4, and $Pb(NO_3)_2$, usually range in size from 2.4 to 6.4 μm.[14] The mass median diameters of lead-containing metal fume in a nonferrous foundry are around 8 to 10 μm.[22] Variation in particle sizes may explain the discrepancies for the ladle attendant. Sampler collection of these particles may be inefficient above a critical particle size,[21] and heavy particles of the same velocity or size as light ones will better overcome the positive pressure at the respirator exit. This bears further research. Thus the conflicting protection factors for the different metals in Table II cannot be ascribed to a single obvious parameter.

This is one of the first studies to assess directly protection factors towards Pb, Cu or Zn of positive pressure respirators during actual working conditions for workers in a brass foundry. Ponnambalam[13] reported levels of 0.47 to 1.22 mg Pb/m^3 to cause blood lead (PbB) levels of 53 to 93 $\mu g/dL$. Single or double cartridge negative pressure respirator usage in that study was estimated by the present author to provide protection factors ranging from 1 to 8, based on the lead in air/maximum air lead ratio. The maximum air lead level was estimated by Ponnambalam[13] from the PbB/air lead correlation of Williams, *et al.*[14]

Field studies of half-mask negative pressure respirators in a variety of industries including copper melting, cotton processing, and paint spraying have reported median protection factors ranging from 2.9 to 43.[15-19] These protection factors are similar to those observed in this study for the AH3 model. Coal miners exposed to coal dust had effective protection factors of half-mask respirators which exceeded 10 for only 11% of the respirators.[18] The median effective protection factor was 3.2. Smith, *et al.*[19] investigated the effective protection factors provided by qualitatively fitted double cartridge filter respirators (Welsh 7500-8) for a population of nine workers exposed to cadmium as CdO fume in a cadmium production facility. The median effective protection factor was around 5.6, with 22% of the factors being above 10, and with one value of 103. These values also included dilution with exhaled air, unlike the present studies. All these field values, including our own, are to be compared with the much higher median protection factors attained in laboratory studies by Barghini and Wilmes[20] who found values ranging from 200 to 2000 for half-mask respirators tested on an anthropometrically weighted test panel.

The above results, therefore, indicate that field studies must be done to assess the true protection of respirators under working conditions rather than laboratory experiments alone. It is also necessary to evolve a more realistic set of exercises for respirator evaluation. It is evident that engineering controls, *e.g.*, the fashioning of a lid for the ladle in this study, and the provision of a small, cooled, independently ventilated room for rest periods, may be required in conjunction with respirators to protect worker health, and that engineering controls may ultimately offer the best solution to worker protection.

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Authors' Note

On March 3, 1983, the U.S. Department of Health and Human Services issued a respirator information notice that both the 3M Powered Air Purifying Respirator (TC-21C-246) and the Racal Powered Air Purifying Respirator (TC-21C-212) could not be relied upon to attain protection factors of 1000 for lead dust/fume, and silica flour under workplace conditions. Approximately 95% of the workplace protection factors for both models for lead dust/fume and using tight-fitting face pieces exceeded 33, and 98% were below 1000. The geometric mean for both was 182.